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Switching on the Sun

Something as seemingly simple as saran wrap. Thin—very thin —layers of stacked plastic sheets could represent the future of electricity. Those thin sheets are conductive polymers with embedded nanorods or quantum dots of semiconductor material that one day may produce electricity from the sun to power homes and businesses.

Fanciful? Perhaps. But plastic solar cells serve as a benchmark for how far we've come since the middle of the 1970s, when solar electricity was only a reality for powering satellites and was still too expensive for uses on Earth. And they are a harbinger of what is to come. The first steps toward plastic solar cells have been taken by researchers at universities and research organizations under an NREL program. Scientists can convert from 2% to nearly 5% of sunlight to electricity (depending on the approach). And prospects look good for bumping conversion efficiencies well beyond 10%, toward viability and toward solar electricity that could someday cost less than 2¢/kWh.

BP Solar's new semi-transparent amorphous silicon modules—developed through participation in the Amorphous Silicon National Research Team—are used to provide power to run pumps, lights, and other loads at BP gasoline stations.

This is part of the promise of the emerging solar electric revolution. Solar electricity is the ultimate distributed energy. Solar electric systems can provide electricity anywhere in any amount—from a few watts to billions of watts. Solar electricity is coming to America along two general technological pathways. One of these pathways is photovoltaics (PV or solar cells)—in which photons dislodge electrons in solid-state materials to directly convert sunlight to electricity. The other is concentrating solar power—in which the heat of concentrated sunlight is used to generate electricity.

Nanorods and Quantum Dots

NREL and its research partners have been investigating semiconductor-related nanotechnology since the early 1980s. In 1984, NREL researchers were among the first to report on quantization effects in nanosize semiconductor particles related to solar cells. Today, this pioneering research is showing promising results in the form of nanorod and quantum-dot solar cells.

Nanorods are semiconductor "wires" that are a few nanometers wide and up to 100 nanometers long (a nanometer is one-billionth of a meter). Embedding nanorods in conductive plastic sheets results in thin, flexible solar cells. The nanorods absorb light of specific wavelengths to generate electrons and holes (vacancies in the material that move around similar to electrons). The rods conduct the electrons along their length. Holes are transferred to the plastic, which conducts them to an electrode.

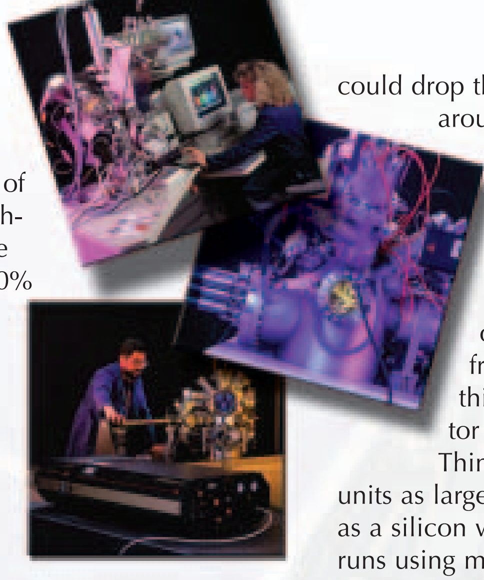
Two innovative organic solar cells: The top cell employs nanorods of cadmium selenium embedded in conductive polymer. The bottom cell also uses a conductive polymer substrate, but with extremely thin embedded multilayers of organic molecules.

Quantum dots are dots of semiconductor material containing from just a few atoms to tens of thousands of atoms. Like nanorods, dots can be embedded in conductive polymer, or can be used with other materials, such as titanium dioxide. By varying their size, quantum dots can be tuned to absorb specific wavelengths of light and so represent an avenue toward multi-multijunction devices that could theoretically convert as much as 66% of sunlight to electricity.

Solar-Cell Generations

In 1977, when NREL first began its research on solar cells, the world produced less than 50,000 watts of solar cells; they were based on crystalline silicon wafer technology, and most were for use in space. Today, we are developing and exploring a wide range of material and device technologies, the worldwide market is growing by 30% to 40% per year and is fast approaching 500 million watts per year.

Several things are spurring this growth. First is the search for dependable alternative electricity systems that can be used in a distributive sense—to generate electricity at the point of demand—and that can provide security against supply disruptions, sabotage, or swings in energy prices. Second, PV has become a dependable and versatile technology. Third, the cost of electricity from solar cells has declined more than fourfold since 1980 and continues to decline.



NREL has built what may be the world's finest center for measuring and characterizing photovoltaic and renewable energy materials and devices. Shown here are just a few of the dozens of sophisticated instruments used in the center: an XPS, for chemical-bonding information; a TOF SIMS, for surface and compositional analysis; and an STM, for nanoscale imaging and spectroscopic studies.

In America today, tens of thousands of homes and businesses use PV electricity. By 2030, this number could increase to tens of millions, with PV providing 150 to 200 billion watts of power. "To get there," says Larry Kazmerski, director of NREL's National Center for Photovoltaics, "solar cells and modules must get much cheaper, get much more efficient, or both." NREL and its research partners in industry and universities are helping to push PV toward the cheaper and better along several generations.

1st Generation—Silicon Wafers. This path is one of continuous incremental improvements. Silicon-wafer technology uses "thick" (150- to 300-microns) wafers of crystalline silicon cells connected together to form modules and sandwiched between sheets of glass. In 2001, this mature technology constituted about 90% of the solar-cell market. Costs are dominated by the relatively high cost of semiconductor material. Module conversion efficiencies are expected to increase from today's 13% to beyond 16%. As a result of this and improvements in manufacturing technology, this path could drop the cost of solar electricity to around 7¢/kWh by 2010. This is good for the short run, but not as low as we can go in the long term.

2nd Generation, Part 1—Thin Films. This technology uses films of semiconductor material that are from 1 to 10 microns thick. Hence, thin films use far less semiconductor material than does wafer silicon. Thin-film devices can be made in units as large as a meter—100 times as large as a silicon wafer—and can be made in large runs using mass-production techniques. Thin films are versatile and are leading the charge for today's specialty, building-integrated applications. For example, thin-film modules can be made translucent, as shingles for roofs, and incorporated into architectural glass.

NREL has been researching thin-film materials since the late 1970s. Of these, three have emerged—amorphous silicon, copper indium diselenide, and cadmium telluride. Amorphous silicon has been building market share since the 1980s. The other two are relative newcomers to the market. Currently, the efficiency of commercial thin-film modules ranges from 5% to 11% (depending on the material and device structure), and costs are competitive with those of wafer silicon. But prospects are promising. For example, by layering thin-film materials on top of each other so that different layers capture and convert different portions of the solar spectrum—a concept known as "multijunction"—modules could eventually convert more than 15% of sunlight to electricity. This, along with improved production techniques, could drop electricity costs below 4¢/kWh—competitive with most conventional electricity, but with built-in advantages.

2nd Generation, Part 2—Multijunction. A third path is through high-efficiency multijunction. This is similar to the thin-film multijunction described above, except that it relies on semiconductor materials that could result in very high efficiencies. These are materials primarily from Groups III and V

The 4 Times Square building in Manhattan uses thin-film PV panels to supply 15 kW of power to supplement the building's electricity needs. Located on the top 14 floors on the south and east sides of the building, the PV panels are integrated into the spandrel—the opaque area of the façade below rows of windows—in 60-inch-wide strips. (Andrew Gordon Photography.)

of the Periodic Table of the Elements—such as gallium arsenide, indium phosphide, and gallium indium phosphide. Thus far, the best device is a three-layer (three-junction) cell that converts up to 34% of sunlight to electricity (see sidebar "From Space to the Earth"). Typically, this approach uses concentrated sunlight, where lenses focus large amounts of solar energy onto a small cell.

3rd Generation—Beyond the Horizon. To drastically lower the cost of solar electricity—below 2¢/kWh—you have to leapfrog the conventional to the innovative. This third generation is mostly at the basic research stage, but these are concepts that auger very low cost or very high efficiency (three or four times that of current state-of-the-art silicon-wafer cells). The plastic cells mentioned above are part of this future generation. Other concepts include:

- Hot-carrier solar cells (which capture and convert electrons in excited states before they return to stable energy levels).
- Cells that can convert a photon into two or more electron-hole pairs to carry the current, in contrast to conventional cells, in which a photon produces one electron-hole pair.
- Quantum-dot solar cells, in which nano-sized dots of semiconductor material are tuned to capture and convert specific wavelengths of the solar spectrum (see sidebar "Nanorods and Quantum Dots").

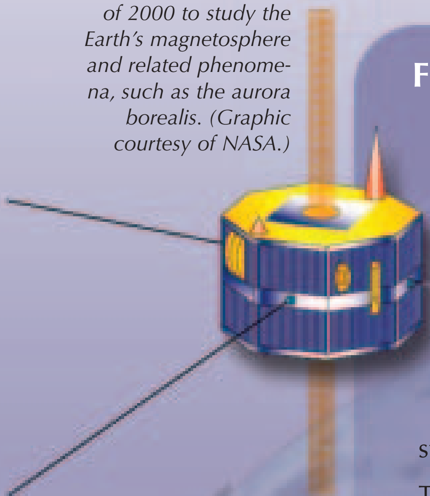
Concentrating Solar Power

Solar Troughs. When the federal research program began in the late 1970s, there were no concentrating solar power systems in existence. By 1991, thousands of acres of solar troughs in the Mojave Desert were generating 354 MW of power, thanks in large part to R&D by national laboratories (including NREL, along with Sandia National Laboratories) and industry that dropped costs three- to five-fold by 1990.

A solar trough uses parabolic-shaped mirrors to concentrate sunlight onto a receiver (a heat-collection element) running along the focus of the curved surface. For latitudes within the United States, the trough tracks the sun from east to west to maximize solar energy captured by the receiver. This concentrated solar energy heats oil flowing through the receiver, which is then used to generate electricity via a conventional steam generator.

At 12¢ to 14¢/kWh, the troughs in the Mojave Desert produce electricity more cheaply than other solar electric alternatives. As such, they provide supplementary power to a highly competitive market—that of peaking and intermediate-load power for grid-scale applications. Moreover, with a federal R&D strategy that will help reduce the cost of electricity to about 6¢/kWh by the end of the decade, solar troughs will be able to compete directly with conventional power generation for peaking markets. This strategy may also reduce trough electricity to less than 5¢/kWh by 2020, making it com-

The IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) satellite was one of the early satellites to use the new III-V multijunction cells to provide power for operations. IMAGE was launched in March of 2000 to study the Earth's magnetosphere and related phenomena, such as the aurora borealis. (Graphic courtesy of NASA.)



From Space to the Earth

For decades to come, satellites launched into Earth orbit will depend on power provided by innovative solar cells pioneered by NREL scientists and perfected in partnership with industry. These devices are lighter, more powerful, and more efficient than all previous solar-cell power systems shot into space. And more durable—they will easily withstand 15 years of particle storms sent by sun and solar wind.

The devices are double- and triple-junction cells based on gallium indium phosphide, gallium arsenide, and germanium. They convert about 30% of sunlight to electricity, far greater than other space solar cells. They're not just good for space, though. NREL and Spectrolab—an industrial partner—redesigned the cell for use on Earth under concentrated sunlight. This Earth-bound version, which is especially suited for use under direct sunlight, can convert up to 34% of sunlight to electricity, a world record for photovoltaics.

This research resulted in two prestigious R&D 100 Awards—one for the space cell and one for the redesign that brought it to Earth. But even more important, it has led to breakthroughs in understanding solid-state materials, their growth processes, and their optical and electronic properties. This understanding is leading the advance toward devices with four and more junctions and efficiencies beyond 40%.

The Impact 2000 home in Massachusetts uses a 4.5-kW utility-interactive PV system. It also incorporates many other energy efficiency and renewable energy features—solar hot water, super insulation, passive solar heating and cooling, and an earth-coupled, geothermal heat pump.

petitive for central-station power. Toward these ends, R&D will focus on:

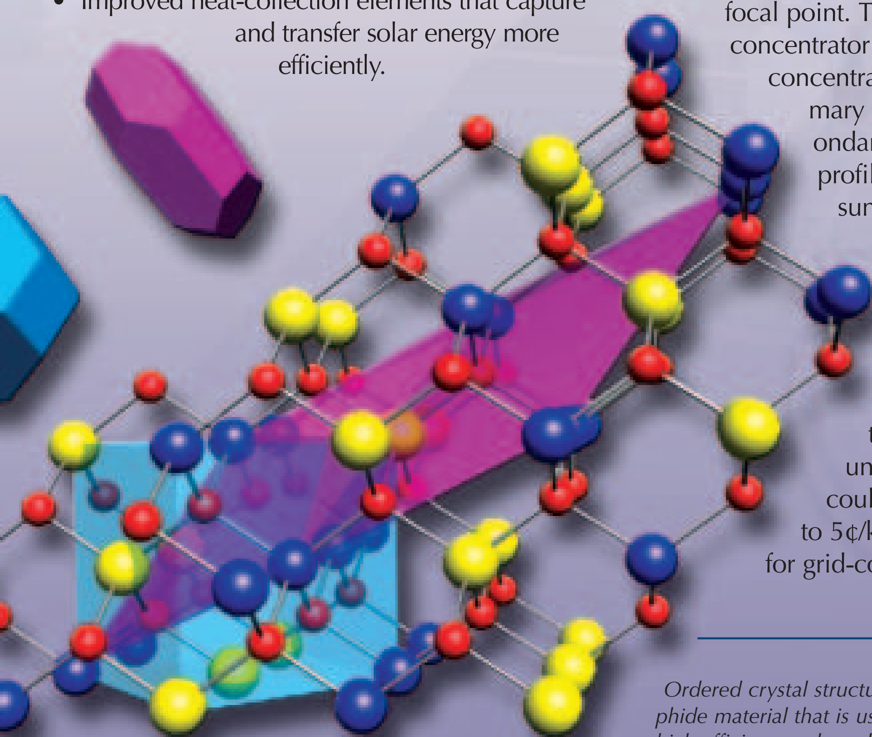
- A near-term capability to store solar energy for long periods—such as in a molten salt medium—which would allow energy to be captured while the sun shines and electricity to be generated and dispatched while the sun is not shining. The ability to dispatch energy when and where needed will extend the utility of concentrated solar power and reduce costs.
- Longer-term advanced fluids for thermal storage of solar energy—fluids whose properties would enable easy storage and retrieval of energy, at optimal working temperatures.
- Better, lighter, cheaper reflecting surfaces—such as very thin glass or flexible, high-density aluminum—laminated on a flexible substrate.
- Improved heat-collection elements that capture and transfer solar energy more efficiently.

The Perfect Dish. For greater modularity, one can turn to dish concentrator systems, which use mirrors or reflective membranes in a dish-shaped configuration to reflect and focus the sun onto a small area, and a receiver/engine located at the focal point to generate electricity. When used with a Stirling heat engine to convert solar heat energy to electricity, a dish concentrator can provide electricity in units that range in size from 3 kW to 25 kW.

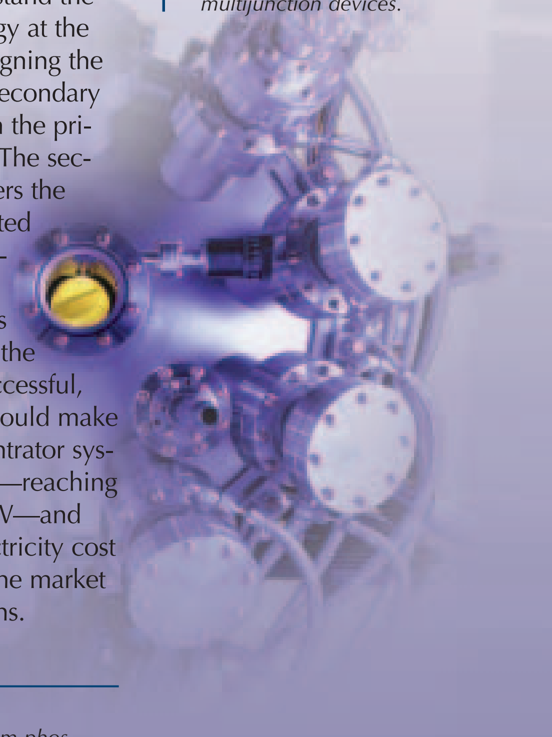
Although today's systems can convert nearly 30% of sunlight to electricity and although R&D by NREL, Sandia National Laboratories, and industry has dropped costs and improved reliability significantly since the early 1980s, the only systems in use today are those being built to test and demonstrate their viability. But large markets are just around the corner.

Once we prove the ability of systems to operate reliably, economies of scale could reduce the cost of current designs to 8¢-10¢/kWh and open the distributed generation market. R&D—especially that for developing a more reliable, efficient, and long-lasting engine system—will help drop costs even more.

Coming Full Circle. An innovative research direction combines the solar dish concentrator with that of a highly efficient silicon or multijunction PV module placed at the focal point of the concentrator. NREL researchers are engineering the PV module so that it can withstand the high concentration of solar energy at the focal point. They are also redesigning the concentrator concept, using a secondary concentrator in tandem with the primary dish concentrator. The secondary concentrator alters the profile of the concentrated sunlight so that the solar flux will be uniform across the surface of the module. If successful, this concept could make the dish concentrator system more modular—reaching units as small as 1 kW—and could help reduce electricity cost to 5¢/kWh, opening up the market for grid-connected substations.



Ordered crystal structure of the gallium indium phosphide material that is used in double- and triple-junction high-efficiency solar cells.



Molecular beam epitaxy (MBE) is one of scores of systems NREL researchers use to grow, develop, design, and monitor PV cells and devices. The MBE, in fact, is integral to the growth and design of NREL's successful III-V family of high-efficiency multijunction devices.